Review on Adjustable Speed Drive Techniques of Matrix Converter Fed Three-Phase Induction Machine

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***Abstract*—Adjustable Speed Drive (ASD) fed Matrix Converter is an interesting topic and is widely discussed in several articles. ASD provides many advantages, especially in the industrial sector because it increases work efficiency so as to reduce production costs. The induction machines construction is sturdy and its relatively inexpensive maintenance makes it more desirable in industrial process applications. Whereas the Matrix Converter (MC) construction without dc-link capacitors makes it more compact compared to conventional converters. This article discussed the ASD control modulation technique by using MC on a three-phase induction motor.**

Keywords---Adjustable Speed Drive (ASD), Matrix Converter (MC), Three-Phase Induction Machine, Space Vector Modulation

I. INTRODUCTION

Adjustable Speed Drive (ASD) on the induction machine is an interesting topic and is widely discussed in several articles. ASD is an electromagnetic system that is suitable to be implemented in industrial applications [1]. The application of ASD on an induction machine provides an increase in power consumption efficiency, so as to provide benefits, especially in the industrial sector and other sectors that use induction machines as a driving motor [2], [3]. ASD provides a continuous speed control circuit on an induction machine. This system optimizes industrial processes and reduces production costs and energy consumption costs.

An induction machine is an interesting choice in the industrial field because it is easy to maintain and a simpler and more robust physical form [4]. Another advantage of the induction engine is the DC engine in terms of size, efficiency, cost, service life and maintenance [5]. Induction machines are generally more desirable in industrial applications than other types of machines. The induction machine has a constant input supply voltage and the frequency operates at a constant speed. Nearly 60% -65% of the electricity resources are consumed by electric motor drives. In conventional methods, induction motors are combined with other equipment which causes energy waste. Motor speed control by the converter saves energy up to 20% [6]. Therefore a system that is capable of controlling machine speed is needed.

Induction machine speed is controlled by changing the frequency and voltage values. The most promising possibility to change motor speed is to vary the frequency. The current is also controlled by voltage so it offers the possibility to control voltage and change the good frequency [7]. This is achieved by using conventional inverter and converters. The AC-DC-AC converter consists of a controlled or uncontrolled converter, inverter and a dc-link capacitor connected between the converter and the stage inverter. The input supply is connected to the converter while the load is connected to the inverter side [8]. However, the use of conventional inverters and converters as the induction engine speed controller has various problems, among them, are expensive main components and relatively large physical structures. In 1980, Alesina and Venturini introduced an AC-AC converter topology composed of nine bidirectional switches in the form of a 3*3 matrix known as the Matrix Converter (MC), which is more efficient compared to conventional AC-DC-AC converters. Modeling results conducted by B. Geetha Lakshmi et al, ASD using MC operates well and reduces interharmonics when compared to conventional AC / DC / AC conversion methods.

The simple MC design, not using large dc-link capacitors as energy storage and ease of control of power factor input makes it an advantage that is more concise and practical. Another advantage of MC is that it has a more dynamic performance compared to conventional AC-DC-AC converters [9]. MC becomes an alternative to back-to-back converters because it converts the AC voltage directly into AC output voltage. The advantage of using MC between is not having a large dc-link capacitor, providing bi-directional power flow, input current and output in the form of sinusoidal waves, input power factor is controlled, high power density, four quadrant operations, regeneration capabilities, concise and simple design [10], [11]. The MC parts are shown in Figure 1. The first part is a three-phase AC power supply. The second part is the MC input filter which functions to filter the input current and produce the capacitive voltage source needed by the MC. The third part is the MC itself.

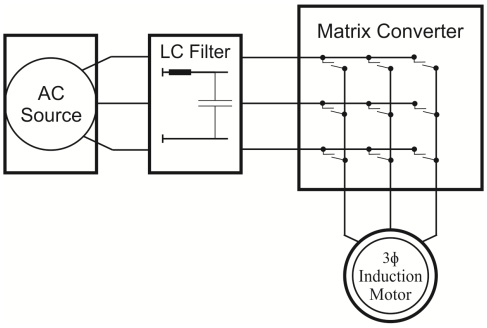

Figure 1. General Matrix Converter

Applications in the industry require AC-AC power conversion. AC-AC converters take power from one AC system and send to another AC system in the form of a wave or amplitude and frequency or phase difference. The AC-AC converter is clarified into two categories: Direct converter and Indirect converter [12]. In general, MC topology is divided into two major parts, namely Direct Matrix Converter (DMC) and Indirect Matrix Converter (IMC). An ASD control with MC on three-phase induction machines uses several modulation strategies. This article discusses the strategy of space vector modulation (SVM) for the control of three-phase induction machines in DMC and IMC.

II. SPACE VECTOR MODULATION ON DMC

The DMC shown in Figure 2 does not require two AC-DC and DC-AC conversion stages. This converter converts AC directly into AC and hence, it eliminates the unnecessary conversion processes [13]. DMC contains a bidirectional matrix switch that interconnects each phase of input with output. Three-phase induction motor connected to the DMC with nine bidirectional switches. The symbol of S_{ij} (i=a, b, c and j=A, B, C) represents the ideal bidirectional switch, where i is the output voltage index and j is the input voltage index. Then $[V_i]$ is used as a vector from the input voltage.

$$V_i = V_{im}\begin{bmatrix}\cos(\omega_i t)\\ \cos\left(\omega_i t - \frac{2\pi}{3}\right)\\ \cos\left(\omega_i t - \frac{4\pi}{3}\right)\end{bmatrix}$$

Then $[V_0]$ is used as a vector from the output voltage.

$$V_0 = V_{0m}\begin{bmatrix}\cos(\omega_0 t)\\ \cos\left(\omega_0 t - \frac{2\pi}{3}\right)\\ \cos\left(\omega_0 t - \frac{4\pi}{3}\right)\end{bmatrix}$$

$$V_0=[M][V_i]$$

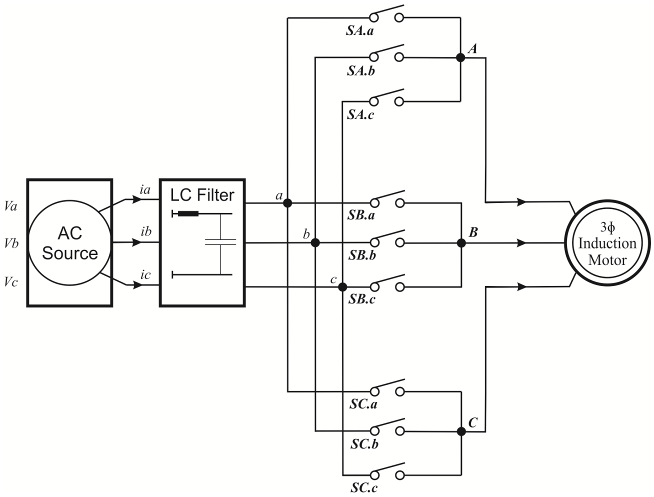

Figure 2. DMC Topology

When the input current is $[I_i]$ then the output current is

$$I_i=[M]^T[I_0]$$

$[M]^T$ represents the transposed of the matrix [M]. When commuting, bidirectional switches must meet the following conditions.

- Each input phase voltage is not connected to the same output line to avoid short-circuit.
- The output phase is not opened to prevent interference with inductive loads.

By defining the transfer function every bidirectional switch is as

$$S_{ij}(t)=\begin{cases}1, S_{ij} \text{ closed}\\ 0, S_{ij} \text{ open}\end{cases}$$

Where, i ϵ {a,b,c}, j ϵ {A,B,C}

These two conditions are expressed by

$$S_{aj}+S_{bj}+S_{cj}=1; j \epsilon \{A,B,C\}$$

Under these circumstances, 3*3 MC only allows 27 switching of 512 combinations. Each T only switches one S_{ij} (j = a, b, c) to ensure a closed loop load current. The switching frequency $f_s=f_\omega/2\pi$ must have a value twenty times higher than the maximum input $f_i f_0$ ($f_s \gg 20xMax(f_i f_0)$).

During the T period (sequential period) which is equal to $1/f_s$, the amount of conduction time used to synthesize the same output phase must be the same as T_a. Now the time T_{ij} is called modulation is defined $t_{ij} = m_{ij}.T_s t_{ij} = m_{ij} T_s$.

According to [14], Direct Matrix Converter topology has the following features:

- It has a sinusoidal input current and output voltage
- It uses bidirectional switches that allow energy regeneration to the source.
- It allows adjustment of the input power factor of the converter, power factor is easily achieved.
- It is more compact on physical size and more cost-effective because it does not use DC energy storage links.

Research conducted by [15] controls SVM in DMC by applying the following formula:

$$\underline{x} = \frac{2}{3}\left(x_1 + a.x_2 + a^2.x_2\right) \text{ and } a = e^{2\frac{2\pi}{3}}$$

The output voltage vector reference $\underline{v_0}$ and the input current $\underline{i_i}$ are represented in the following formula:

$$\underline{v_0} = \frac{2}{3}\left(v_a + a.v_b + a^2.v_c\right) = v_0.e^{j\alpha_0}$$

$$\underline{i_i} = \frac{2}{3}\left(i_A + a.i_B + a^2.i_c\right) = I_i.e^{j\beta_i}$$

The specified switching condition produces 27 configurations for the 3*3 structure on the MC. The reverence voltage vector $\underline{v_{0^*}}$ is obtained from two adjacent vector directions. This direction corresponds to the configuration pair ± 1, ± 2, ± 3, ± 7, ± 8, ± 9. Similarly the current reference vector $\underline{i_{i^*}}$ is obtained from two directions located on both sides of the vector and obtained with a configuration of ± 1, ± 4, ± 3, ± 6, ± 7, ± 9. The chosen configuration pair is that which appears from both lists, in this case, the configuration pair is ± 1, ± 3, ± 7, ± 9. Therefore the four configurations used depend on the K_v sector where the desired output voltage $\underline{v_{0^*}}$ vector and K_i sector are the reference vectors of the input current $\underline{i_{i^*}}$.

Stationary and voltage vector representations that are recorded K_v for voltage and K_i for current are shown in Figure 3.

The duty cycle is calculated by the following formula:

α_0 is the angle between the desired output voltage vector and the line for the sector.

β_i is the angle between the desired input current vector and the line for the vector.

$\cos(\emptyset_i)$ is the input power factor.

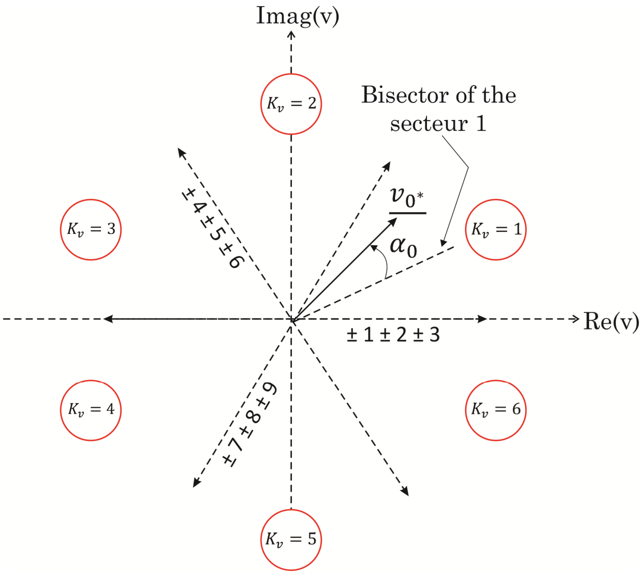

Figure 3. The direction of output voltage vector and output current vector

$$\begin{cases} \delta_I = (-1)^{K_v+K_i} . \dfrac{2}{\sqrt{3}} . q . \dfrac{\cos\left(\alpha_0 - \frac{\pi}{3}\right)\cos\left(\beta_i - \frac{\pi}{3}\right)}{\cos(\emptyset_i)} \\ \delta_{II} = (-1)^{K_v+K_i+1} . \dfrac{2}{\sqrt{3}} . q . \dfrac{\cos\left(\alpha_0 - \frac{\pi}{3}\right)\cos\left(\beta_i + \frac{\pi}{3}\right)}{\cos(\emptyset_i)} \\ \delta_{III} = (-1)^{K_v+K_i+1} . \dfrac{2}{\sqrt{3}} . q . \dfrac{\cos\left(\alpha_0 + \frac{\pi}{3}\right)\cos\left(\beta_i - \frac{\pi}{3}\right)}{\cos(\emptyset_i)} \\ \delta_{IV} = (-1)^{K_v+K_i} . \dfrac{2}{\sqrt{3}} . q . \dfrac{\cos\left(\alpha_0 + \frac{\pi}{3}\right)\cos\left(\beta_i + \frac{\pi}{3}\right)}{\cos(\emptyset_i)} \end{cases}$$

The duration of the zero vector to complete the modulation period is given with the following formula:

$$\delta_0 = 1 - (\delta_I + \delta_{II} + \delta_{III} + \delta_{IV})$$

III. SPACE VECTOR MODULATION ON IMC

The IMC shown in Figure 4 has a rectification process (AC-DC) and an inversion process (DC-AC). In other words the IMC performs a two-stage conversion. This converter has a rectifier and inverter but does not have the DC storage energy. IMC is classified based on topology and number of devices used. In general, IMC consists of a bidirectional current rectifier following a standard Voltage Source Inverter (VSI). IMC gets a lot of attention and there are some innovative topologies that reduce the number of switches, namely sparse, very sparse and ultra-sparse MC [16].

It is assumed that the three-phase input voltage is given in the following equation:

$$V_{sa}=V_m\cos\theta_a = V_m\cos(\omega_i t)$$

$$V_{sb}=V_m\cos\theta_b = V_m\cos\left(\omega_i t-\frac{2\pi}{3}\right)$$

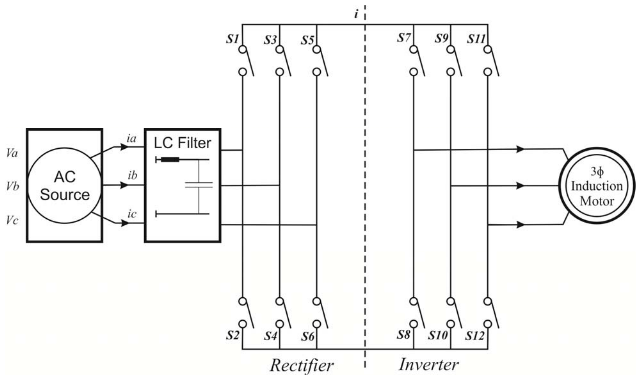

Figure 4. IMC Topology

$$V_{sc}=V_m\cos\theta_c = V_m\cos\left(\omega_i t+\frac{2\pi}{3}\right)$$

On the load side:

$$i_A=I_0\cos\theta_{0t} = I_0\cos(\omega_0 t+\varphi_0)$$

$$i_B=I_0\ \cos\left(\omega_0 t+\varphi_0-\frac{2\pi}{3}\right)$$

$$i_B=I_0\ \cos\left(\omega_0 t+\varphi_0+\frac{2\pi}{3}\right)$$

The final formula shows the current in the load. Where ω_0 and ω_i are the frequency of the input and output angles. Whereas φ_0 is the initial electric angle of the phase A output current. Then V_m and I_0 are the peak amplitude of the input voltage and the output current.

However, the IMC at low voltage transfer ratios still has several problems and methods need to be developed to improve the output waveform so as to optimize operating performance. The method to improve the output waveform is categorized into two, namely the control algorithm, which is used to compensate for various non-linear factors, and the modulation strategy. In commutation and semiconductor loading schemes, IMC has a more simple commutation because of its two-stage structure, but it sacrifices more electrical devices connected and produces higher semiconductor losses and lower efficiency compared to DMC.

According to the research conducted by [17] applying SVM to IMC, the space vector diagram in SVM is shown in Figure 5, where six active vectors switching $(\vec{i}_1\sim\vec{i}_6\ or\ \vec{u}_1\sim\vec{u}_6)$ dividing the complex field into six sectors. The three desired output voltages or input current vectors are located in certain sectors and are synthesized by two adjacent active vectors and zero vectors. Then the duty cycle vector is calculated according to the volt-second balance or the balance of the capacitor charge.

Assume the vector input voltage is denoted as $\vec{u}_i = U_{im}e^{j\alpha_i}$ where U_{im} and α_i is the position of amplitude and angle $\vec{u}_i$. The desired vector input $\vec{i}_i = I_{im}e^{j\varphi_i}$ lying in the sector I= $\left(\varphi_i\epsilon\left[-\frac{\pi}{6},\frac{\pi}{6}\right]\right)$ as shown in Figure 5 (a), the cycle duty vector cycle used is

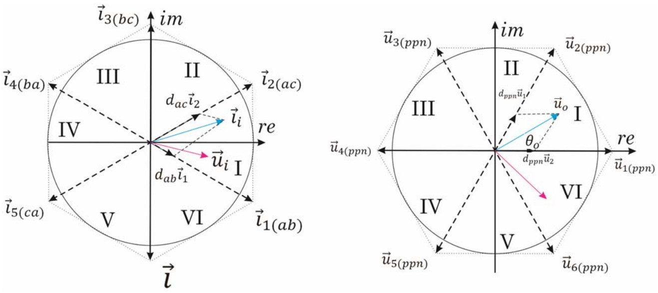

Figure 5. Diagram of space vector on IMC, (a) rectifier stage, (b) stage inverter

$$\begin{cases} d_{ab} = m_i sin\left(\frac{\pi}{6}-\varphi_i\right) \\ d_{ac} = m_i sin\left(\frac{\pi}{6}-\varphi_i\right) \\ d_{r0} = 1-d_{ab}-d_{ac} \end{cases}$$

Where φ_i is the position of the angle $\vec{i}_i$, m_i shows the receiver modifier index, and $0 \leq m_i \leq 1$.

As shown in Figure 5 (b), it is assumed that the desired output voltage vector is $\vec{u}_o = U_{om}e^{j\theta_o}$ is also located in sector I= $\left(\theta_o\epsilon\left[0,\frac{\pi}{3}\right]\right)$, duty cycle the one from the vector used is

$$\begin{cases} d_{pnn} = m_o\ sin\left(\frac{\pi}{3}-\theta_o\right) \\ d_{ppn} = m_o\ sin(\theta_o) \\ d_{i0} = 1-d_{pnn}-d_{ppn} \end{cases}$$

Where θ_o is the angle position $\vec{u}_o$, m_o s the inverter modulation index, and $0 \leq m_o \leq 1$.

A combination of rectifier and inverter modulation process, the final duty cycle is written as

$$\begin{cases} d_{ab,pnn} = d_{ab}d_{pnn} = k\ sin\left(\frac{\pi}{6}-\varphi_i\right)\ sin\left(\frac{\pi}{3}-\theta_o\right) \\ d_{ab,ppn} = d_{ab}d_{ppn} = k\ sin\left(\frac{\pi}{6}-\varphi_i\right)\ sin(\theta_o) \\ d_{ac,pnn} = d_{ac}d_{pnn} = k\ sin\left(\frac{\pi}{6}+\varphi_i\right)\ sin\left(\frac{\pi}{3}-\theta_o\right) \\ d_{ac,ppn} = d_{ac}d_{ppn} = k\ sin\left(\frac{\pi}{6}+\varphi_i\right)\ sin(\theta_o) \\ d_0 = 1-d_{ab,pnn}-d_{ab,ppn}-d_{ac,pnn}-d_{ac,ppn} \end{cases}$$

Where $k = m_i m_o$. o make it simpler, m_o is set to one and all modulation indices used to modulate the inverter are set to one in the following section.

Then to get the desired output voltage and input current, it must be satisfactory

$$k = m_i = \frac{q}{q_{max} \cos(\phi_i)}$$

Where q is the voltage transfer ratio, and $q_{max} \left(\frac{\sqrt{3}}{2}\right)$ shows the maximum linear voltage transfer ratio; ϕ_i is the input power factor angle, and $\phi_i = \varphi_i - \alpha_i$.

Usually, in the rectifier stage, only active vectors are active (eg $\vec{i}_{1(ab)}$ and $\vec{i}_{2(ab)}$) are used to reduce turnover time. The dc-link voltage U_{dc} only consists of two voltage line-to-line input segments U_{ab} and U_{ac}. Therefore, d_{r0} must be distributed to d_{ab} and d_{ac} as follows

$$\begin{cases} d'_{ab} = d_{ab} + d_{r0(ab)} \\ d'_{ac} = d_{ab} + d_{r0(ac)} \\ d'_{ab} + d'_{ac} = 1 \end{cases}$$

where d'_{ab}, d'_{ac} are the duty cycles $\vec{i}_{1(ab)}$ and $\vec{i}_{2(ab)}$ after distribution, respectively; and $d_{r0(ab)}$, $d_{r0(ac)}$ must meet the following limits.

$$\begin{cases} d_{r0} = d_{r0(ab)} + d_{r0(ac)} \\ d_{r0(ab)} \geq 0, d_{r0(ac)} \geq 0 \end{cases}$$

One of the most commonly used ways to distribute zero vectors is that d_{r0} is divided into $d_{r0(ab)}$ and $d_{r0(ac)}$ in proportion as

$$\begin{cases} d_{r0(ab)} = \dfrac{d_{ab}}{d_{ab} + d_{ac}} d_{r0} \\ d_{r0(ac)} = \dfrac{d_{ac}}{d_{ab} + d_{ac}} d_{r0} \end{cases}$$

IV. COMPARISON BETWEEN DMC AND IMC FED THREE-PHASE INDUCTION MACHINE

The main strategy of ASD driven by the MC is to maintain the current and engine flux at the desired value [18]. In the case of induction motor control, DMC and IMC have several differences in output voltage and power losses that affect the efficiency of the motor. DMC has better supply current and voltage transfer characteristics, smaller voltage losses, and losses. The sinusoidal output wave needed for the working conditions of the ASD system is better. DMC works effectively when given a large modulation index. But when working at low voltages, IMC has superior performance [19]–[21]. Comparison between DMC and IMC in three-phase induction machines is seen in Table 1.

Table 1. Comparison between DMC and IMC

ASD on Induction Machine	DMC	IMC
Supply Current Quality	HIGH	LOW
Voltage Loss	LOW	HIGH
Power Loss	LOW	HIGH
Low Voltage Performance	LOW	HIGH
Large Modulating Index Performance	HIGH	LOW
Sinusoidal Waveforms for working condition	HIGH	LOW

V. CONCLUSION

This article discusses the comparison between DMC and IMC by implementing an SVM strategy when performing ASD on an induction motor. From several articles found, ASD using DMC has advantages compared to IMC. Although DMC dominates the advantages of various characteristics, IMC shows superiority when working at low voltage. This shows that the DMC and IMC have their respective advantages in different conditions. Therefore, the application of ASD on an induction motor uses one of the two topologies that have been discussed according to their individual needs.

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